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AIR ENTRAINMENT IN A JET FLAME STABILIZER IN SUPERSONIC FLOW.(U)
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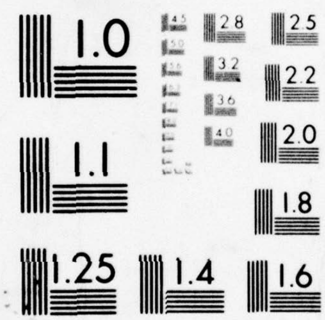

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19 REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: 18 AFOSR - TR-77-0037	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): 6 AIR ENTRAINMENT IN A JET FLAME STABILIZER IN SUPERSONIC FLOW.	5. TYPE OF REPORT & PERIOD COVERED: 9 INTERIM rept.,
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): 10 R.A. COOKSON	8. CONTRACT OR GRANT NUMBER(s): 15 AF- AFOSR -2698 -74
9. PERFORMING ORGANIZATION NAME AND ADDRESS: CRANFIELD INSTITUTE OF TECHNOLOGY ~~SCHOOL OF MECHANICAL ENGINEERING~~ CRANFIELD, BEDFORD MK43 OAL	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: ~~681308~~ 17 16 9711 02 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS: AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA BLDG 410 BOLLING AIR FORCE BASE, D C 20332	12. REPORT DATE: 11 24 Nov 76
	13. NUMBER OF PAGES: 16
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office): 12 18 p.	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report) 14 Memo-AM-52

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

JET FLAME STABILIZER
SUPER SONIC COMPUSTION
SCRAMJET

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An analytical technique, based upon a turbulent boundary layer separation model, has been suggested for determining the amount of air entrained into a fuel jet injected transversely into a supersonic air stream. The amount of air entrained into the fuel jet was found to vary directly with the jet induced blockage. However, the jet induced blockage and hence the amount of air entrained does have a limiting value.

AIR ENTRAINMENT IN A JET FLAME STABILIZER IN SUPERSONIC FLOW

R.A. COOKSON

ABSTRACT

An analytical technique, based upon a turbulent boundary layer separation model, has been suggested for determining the amount of air entrained into a fuel jet injected transversely into a supersonic air stream. *The amount of air entrained into the fuel jet was found* to vary directly with the jet induced blockage. However, the jet induced blockage and hence the amount of air entrained does have a limiting value.

INTRODUCTION

The amount of air entrained into the recirculation zone of a bluff-body flame-holder in subsonic flow controls the flame stability limits. Lefebvre et al (Ref. 1) have suggested a simple method of determining this entrained air mass flow rate. Ignition characteristics of a transverse fuel jet in a supersonic stream are also determined by the amount of air entrained by the jet. In addition, the combustion efficiency is also dependent upon the entrainment. Bier et al (Ref. 2) have demonstrated the importance of the local equivalence ratios within the reaction zone. The region downstream of the injector port contains a fuel rich mixture. They have shown that adding air to this region improves the ignition conditions considerably. If the amount of air entrained into the jet stabilizer is known, then it would be quite simple to design a stabilizer system for use in supersonic streams. To reduce losses, sufficient fuel for stabilization can be injected upstream or downstream to be burnt in the flame propagation zone.

The conditions considered are consistent with those found at the combustor inlet of a scramjet operating at a low hypersonic velocity of about Mach 6 and at an altitude of around 30km. The combustor inlet conditions would typically be Mach 2, static pressure around $1000N/m^2$ and air static temperature approximately 1100^oK.

A hypersonic ramjet must employ supersonic combustion. Although hydrogen is the near ideal scramjet fuel, the choice of hydrocarbon fuels such as methane and kerosene for scramjet applications is also attractive. Liquid hydrocarbon fuels such as kerosene are particularly attractive as storage problems are minimised and if fuel injection from the wall is employed, better penetration into the supersonic flow is obtainable. Unfortunately, for such conditions as mentioned above, the ignition delay for most hydrocarbon fuels is greater than 10ms (compared to 0.1ms for hydrogen). Hence, since the air velocity at the combustor inlet is about 1200m/s, it is obvious that ignition and combustion of hydrocarbon fuels, such as methane and kerosene, would not take place within a reasonable combustor length. Clearly some form of ignition aid is required and hence a knowledge of the air entrainment characteristics is essential.

ANALYSIS

The model The model considered is similar to that proposed by Wu and Aoyama (Ref. 3) determining the penetration height of a transverse jet in an enclosed supersonic stream. The secondary jet acts as an obstruction. The injector port is assumed to be circular. A bow shock wave is produced and the disturbance it produces propagates upstream, causing a separation of the boundary layer. A typical centre line surface pressure distribution in the jet interaction flow field is shown in Figure 1. It can be seen that the surface pressure increases from the ambient to the plateau pressure and then to the peak pressure.

It will be assumed, following Wu and Aoyame (Ref. 3), that the local ambient pressure is the plateau pressure in the case of circular port injection. Since the jet presents an obstruction, various models have been proposed to determine an equivalent bluff body which would give a shock pattern similar to that produced by the jet. The common assumption, that very little mixing takes place near the injector, is not true. The primary stream is squeezed in such a way as to accommodate the area of influence of the secondary jet. This area of influence is clearly the aerodynamic blockage caused by the fuel jet. As far as the phenomenon of flame stablilization is concerned, it is the aerodynamic blockage that matters in determining the flame stability limits (Ref. 4). Lefebvre (Ref. 4) has proposed a method of determining the relationship between the aerodynamic and geometric blockage of bluff bodies in a ducted subsonic air stream. It must be noted that the aerodynamic blockage of a transverse jet should be considered as a form of 'pseudo-blockage', for in the strict sense it is not of the type caused by a bluff body.

Figure 2 gives the details of the flow model. The dotted line denotes the region of influence of the secondary jet. Let m be the amount of air entrained in the secondary (fuel) jet.

Conservation of mass in the primary flow.

$$\dot{m}_1 = \sqrt{\frac{k_1}{R_1}}\, M_1\, A_1\, \frac{P_1}{\sqrt{T_{01}}} \left[1 + 0.5\,(k - 1)M_1{}^2\right]^{\frac{1}{2}} \qquad (1)$$

$$\dot{m}_2 = \sqrt{\frac{k_2}{R_2}}\; M_2\, A_2\, \frac{P_2}{\sqrt{T_{02}}} \left[1 + 0.5\,(k - 1)M_2{}^2\right]^{\frac{1}{2}} \qquad (2)$$

and

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_E \qquad (3)$$

Conservation of energy in the primary flow.

$$T_{01} = T_{02}$$

Conservation of mass in the secondary flow.

For gases

$$\dot{m}_j = \sqrt{\frac{k_j}{R_j}}\; M_j\, A_j\, \frac{P_j}{\sqrt{T_{0j}}} \left[1 + 0.5\,(k - 1)M_j{}^2\right]^{\frac{1}{2}}$$

$$= \sqrt{\frac{k_j}{R_j}}\; A_j\, \frac{P_j}{\sqrt{T_{0j}}} \left[\frac{1 + k_j}{2}\right]^{\frac{1}{2}} \qquad (4.1)$$

for choked flows.

For liquids,

$$\dot{m}_j = A_j\, \rho_j \sqrt{\frac{P_{0j}}{P_1} - 1} \qquad (4.2)$$

It will be assumed that instant vapourization will take place in the case of liquids. Hence the fuel can always be taken to be in a gaseous state after it leaves the injector.

$$\dot{m}_3 = \sqrt{\frac{k_3}{R_3}}\; M_3\, A_3\, \frac{P_3}{\sqrt{T_{03}}} \left[1 + 0.5\,(k_3 - 1)M_3{}^2\right]^{\frac{1}{2}} \qquad (5)$$

Also

$$\dot{m}_3 = \dot{m}_j + \dot{m}_E \qquad (6)$$

$\bar{P}$ is the average pressure acting on the jet. Following Wu and Aoyama, $\bar{P}$ is taken to be the plateau pressure. For a turbulent boundary layer, Mager (Ref. 5) gives,

$$\left.\begin{aligned}
&\frac{\bar{P}}{P_1} = P' \left[\frac{1 + G}{1 + P'G} \right] \\
&\text{where} \\
&P' = 1 + \frac{k_1}{2} M_1^2 \left[\frac{1 - C}{1 + 0.5(k - 1)M_1^2} \right] \\
&\text{and} \\
&G = -0.328 \frac{C\sqrt{M_1^2 - 1}}{1 + 0.5(k_1 - 1)M_1^2 C} \\
&C = 0.55
\end{aligned}\right\} \quad (7)$$

The turbulent boundary layer separation is a weak function of the Reynolds number and hence the Reynolds number effect is neglected.

Conservation of momentum in the primary stream.

$$P_1 A_1 (1 + k_1 M_1^2) = P_2 A_2 (1 + k_2 M_2^2) + \bar{P}A_3 \quad (8)$$

Conservation of momentum in the secondary stream.

$$\bar{P} A_3 = P_3 A_3 (1 + k_3 M_3^2) \quad (9)$$

Also the boundary conditions gives

$$P_2 = P_3 \quad (10)$$

and the geometrical relationship gives

$$A_3 = A_2 + A_8 \quad (11)$$

The pseudo-blockage B can be expressed as

$$B = A_3/A_1 \tag{12}$$

and hence it follows that

$$A_2/A_1 = 1 - B \tag{13}$$

For m = 2.00 and k = 1.32, from equation 7 it follows that

$$\overline{P}/P_1 = 2.210$$

Assuming $k_1 = k_2 = 1.32$ and $P_1 = 101.3\ \mathrm{kN/m^2}$ (14.7 psia) the expression

$$\frac{\dot{m}_E}{\dot{m}_1} = 1.0 - 0.34\left[\Big(70.00 - 24.63B - 0.758\,P_2\,(1 - B)\Big)\Big(6.84 - 2.405\,B + 0.551\,P_2\,(1 - B)\Big)\right]^{\frac{1}{2}} \tag{14}$$

may be derived.

Consider the case of methane fuel and let $k_j = 1.32$. The ratio of molecular weights of air to methane has been taken to be 1.812. From simple mixing rules R_3 and T_{03} can be determined.

Hence,

$$\frac{\dot{m}_3}{\dot{m}_1} = \sqrt{\frac{R_1\ T_{01}}{R_3\ T_{03}}}\left[\frac{m_3}{m_1}\right] B\,\frac{P_2}{P_1}\left[\frac{1 + 0.16M_3^{\ 2}}{1 + 0.16M_1^{\ 2}}\right]^{\frac{1}{2}}$$

$$\frac{\dot{m}_E}{\dot{m}_1} + \frac{\dot{m}_j}{\dot{m}_1} = 0.034\ B\left[\frac{\dfrac{\dot{m}_E}{\dot{m}_1} + \dfrac{\dot{m}_j}{\dot{m}_1}}{\dfrac{\dot{m}_E}{\dot{m}_1} + 1.812\ T\,\dfrac{\dot{m}_j}{\dot{m}_1}}\ (24.60 - 0.758\ P_2)(2.40 + 0.536\ P_2)\right]^{\frac{1}{2}} \tag{15}$$

where

$$\mathcal{T} = T_{0j}/T_{01}$$

For a given $\mathcal{T}$ and $\dot{m}_j/\dot{m}_1$, equations 14 and 15 are of the form

$$\dot{m}_E/\dot{m}_1 = f(P_2, B)$$

Equations 14 and 15 have been solved by trial and error using a computer and the results are shown in Figures 3 and 4.

DISCUSSION

The ignition characteristics of a fuel injected transversely into a supersonic stream are determined by the amount of air entrainment by the fuel jet. This behaviour is similar to that of a bluff body flameholder, the stability characteristics of which are also determined by the air entrainment in the recirculation zone. A turbulent boundary layer separation model was employed in the analytical method used for determining the air entrainment by the fuel jet. Since the transverse jet effectively poses an obstruction to the flow, the concept of pseudo-blockage was introduced. It is clear from Figures 3 and 4 that the air entrainment is directly proportional to the pseudo-blockage (B) for values of blockage below a certain optimum. This is an important result as it agrees with the common assumption for baffle type flame holders that the fraction of total flow which enters the recirculation zone bears a constant relation to the flow which approaches the upstream projected area of the baffles (Ref. 6). An increase in either the ratio (T_R) of fuel to air stagnation temperature or the ratio of fuel to air mass flow rate is found to decrease the air entrainment (Figures 3 and 4).

Lefebvre et al (Ref. 1) have determined, for subsonic flow, the fraction of the total amount of combustible mixture flowing over a bluff body flame stabilizer that is actually entrained in the flame. The air entrainment for the present case is found to vary directly within limits with the pseudo-blockage (Figures 3 and 4). This in constrast to the variation $Bg^{1.5}/(1 - Bg)^{0.5}$ suggested by Lefebvre et al (Ref. 1), where Bg is the goemetric blockage. However it should be noted that comparisons are strictly not valid since blockage in the present case is purely aerodynamic whereas that of Lefebvre et al is geometric. Both predict that increased blockage leads to increased entrainment, although there is substantial difference in the form of dependency.

For a fixed jet stagnation temperature (T_{0j}), an increase in air stagnation temperature (T_{01}) causes a decrease in the ratio

T_{0j}/T_{01}. From Figure 4 it can be seen that this leads to increased entrainment. Lefebvre et al (Ref. 1) found that an increase in the approach stream temperature led to decreased entrainment.

If the dimension of a flame-holder is increased, interference by the duct walls will be more pronounced. Hence a critical blockage is bound to occur beyond which blockage has an adverse effect on stability (Ref. 6). An optimum blockage is seen to exist in the case of air entrainment in a transverse jet (Figures 3 and 4). This optimum blockage is a function of the fuel/air mass flow ratio and of the fuel/air stagnation temperature ratio. It should be noted that although the present analysis is for flow in the absence of combustion, the general behaviour can be considered to be the same for the case with combustion. The stability of the flame will be determined by the factors which affect air entrainment. Hence there is a favourable stabilization effect of the fuel jet blockage, but this blockage cannot be increased without limit.

A surprising aspect of Figure 3 is that a blockage also exists when the fuel mass flow rate is zero ($\dot{m}_j/\dot{m}_1 = 0$). This is obviously fallacious for blockage cannot exist unless fuel is injected. This anomaly arises from the choice of the average pressure acting on the jet. The average pressure ($\overline{P}$) was assumed to be equal to the plateau pressure (Figure 1) which for turbulent boundary layer separation is given by equation 7. As can be seen, the form of equation does not depend upon any jet parameter but is purely a characteristic of turbulent boundary layer separation. The only condition (the matching condition) which must be met in order that equation 7 may be used is that separation should have been induced in the present case when jet injection takes place. This stipulation effectively removes the anomaly. The curve for zero flow rate ($\dot{m}_j/\dot{m}_1 = 0$) has been included just to illustrate this point and does not arise in practice.

It can be observed from Figures 3 and 4 that beyond the optimum blockage, there are two values of entrainment for each value of blockage. This arises from the fact that there are two values of P_2 which satisfy the set of equations in this range. The higher value of P_2 represents the lower branch and the lower the upper branch. Under normal operating conditions when the blockage will be increased from zero, the behaviour will be that predicted by the upper curve.

The analytical equations used are quite general and can be used to predict the air entrainment as well as the optimum blockage for any given conditions and fuel properties.

CONCLUSION

An analytical method has been proposed for determining the air entrainment in a fuel jet injected transversely into a supersonic stream. This method, which is based upon a turbulent boundary layer separation model, has indicated that there is an optimum pseudo-blockage caused by the fuel jet for which the air entrainment is a maximum. Below this value, air entrainment is directly proportional to the jet induced blockage.

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NOMENCLATURE

A = Area

B = Pseudo-blockage

B_g = Geometric blockage

d = Jet diameter

k = Ratio of specific heats

$\dot{m}$ = Mass flow rate

M = Mach number

P = Static pressure

ρ = Density

SUBSCRIPTS

A = Air

E = Entrained

j = jet

o = Stagnation conditions

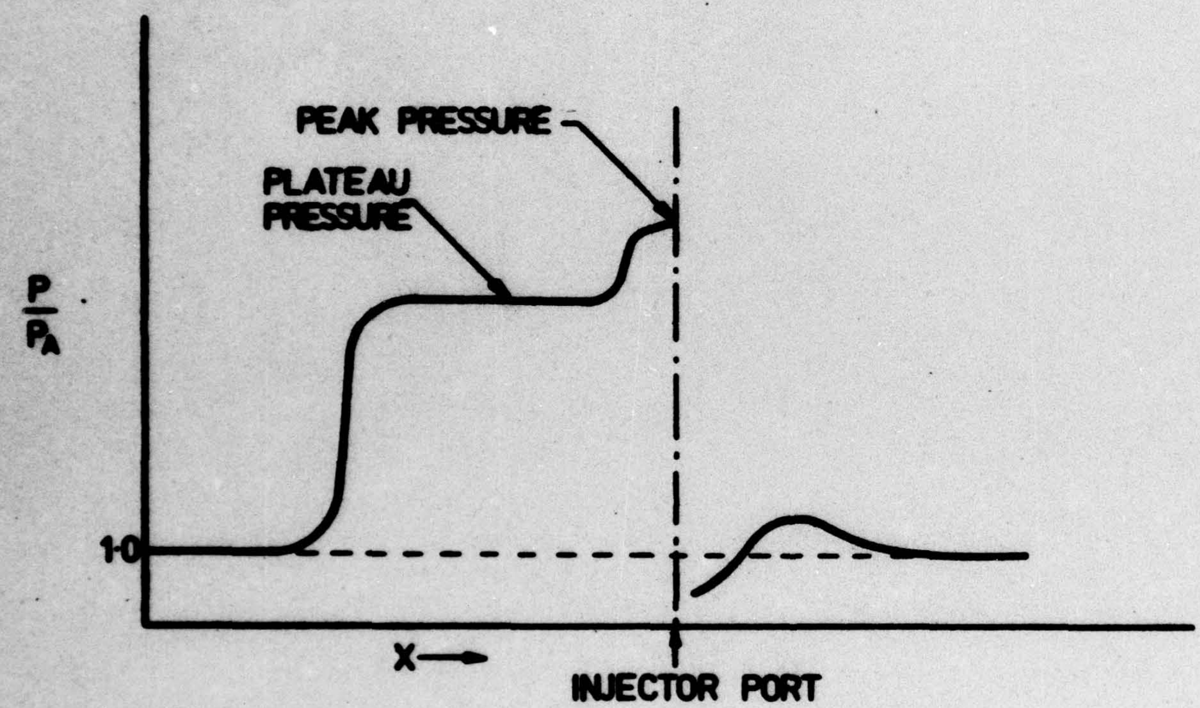

FIG. 1. TYPICAL CENTRELINE SURFACE PRESSURE DISTRIBUTION IN THE FLOWFIELD

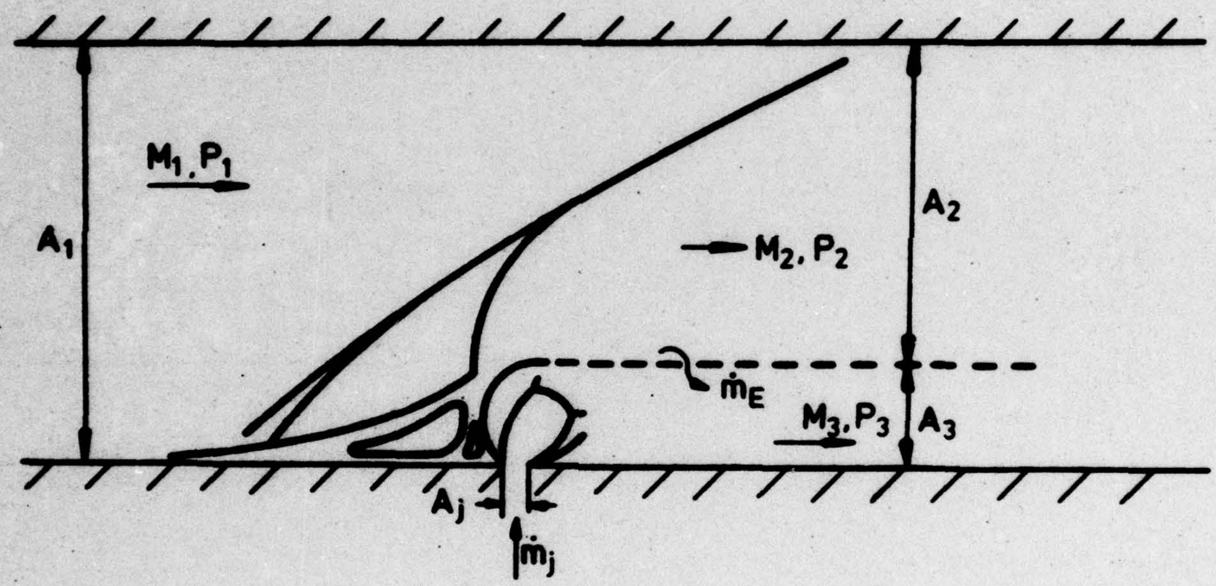

FIG. 2. ENTRAINMENT ANALYSIS

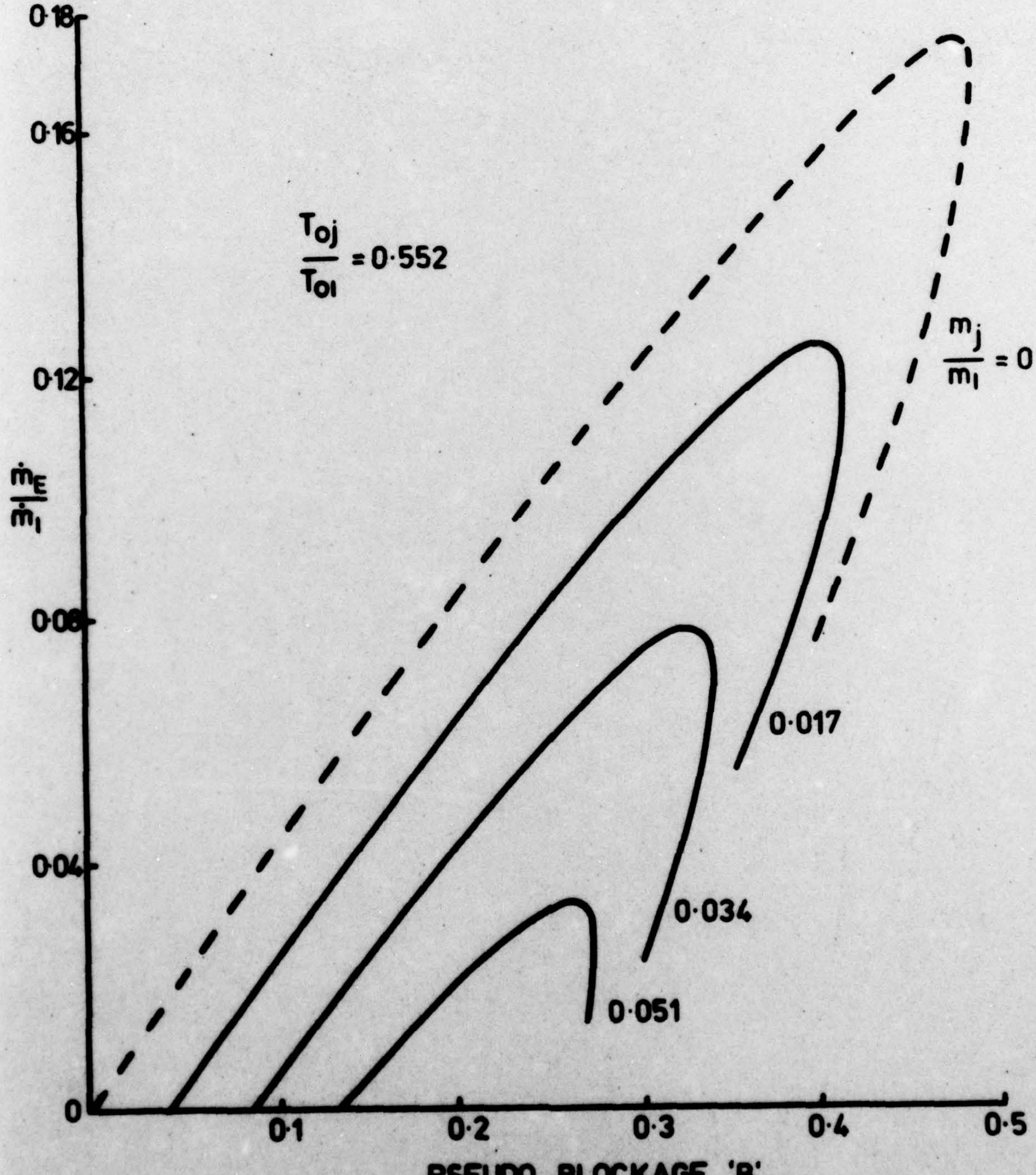

FIG. 3. AIR ENTRAINMENT

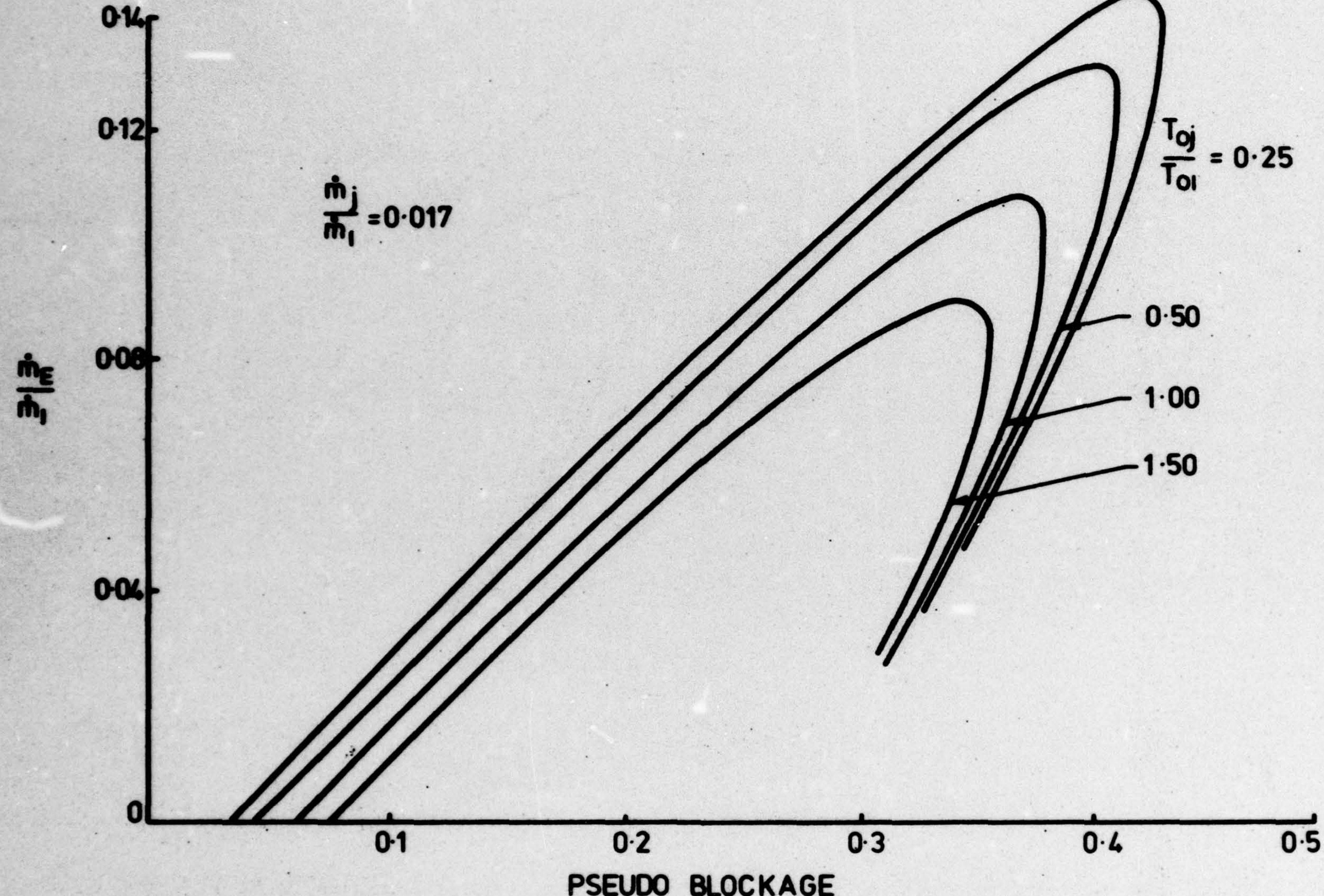

FIG. 4. AIR ENTRAINMENT